

# Dependences of the X-ray luminosity and pulsar wind nebula on different parameters of pulsars and the evolutionary effects

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## Abstract

Dependences of the X-ray luminosity ( $L_x$ ) of young single pulsars, due to ejection of relativistic particles, on electric field intensity, rate of rotational energy loss ( $\dot{E}$ ), magnetic field, period, and some other parameters of neutron stars are discussed. Influence of the magnetic

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field and effects of some other parameters of neutron stars on the  $L_x$ - $\dot{E}$  and the  $L_x$ - $\tau$  (characteristic time) dependences are considered. Evolutionary factors also play an important role in our considerations. Only the pulsars with  $L_{2-10\text{keV}} > 10^{33}$  erg/s have pulsar wind nebula around them. The pulsars from which  $\gamma$ -ray radiation has been observed have low X-ray luminosity in general.

Key words: Pulsar, SNR, X-ray

# 1 Introduction

X-ray luminosity ( $L_x$ ) of single neutron stars strongly depends on the rate of rotational energy loss ( $\dot{E}$ )<sup>1,2,3</sup>.  $\dot{E}$  depends on the spin period ( $P$ ) and time derivative of the spin period ( $\dot{P}$ ) of neutron stars. As there exist many other parameters of pulsars determined from  $P$  and  $\dot{P}$  values,  $L_x$  must also depend on these parameters. This problem has already been analysed using values of  $L_x$  in 2-10 keV band for different groups of pulsars including also the old millisecond pulsars<sup>2</sup>. We also prefer to use the  $L_x$  values in 2-10 keV band, because the absorption is strong in the softer X-ray band and also there must be a contribution of the cooling radiation to the soft X-ray part of the radiation of pulsar which may complicate the problem. Below, using reliable distance values we have analysed in detail the dependence of  $L_{2-10\text{keV}}$  on different pulsar parameters for young single pulsars for which the radiation is related to ejection of relativistic particles. In this investigation we have also used the values of pulsar radiation in 0.1-2.4 keV band and the radiation of pulsar wind nebulae (PWNe) in both bands. Special attention has been paid to the evolutionary factors. There exist many pulsars with large values of  $\dot{E}$  and small values of age from which no X-ray radiation has been observed. Below, we have also discussed possible reasons of this.

## 2 Dependences of X-ray radiation of pulsars and their wind nebula on different parameters of pulsars

For the pulsed radio emission to occur and in order to produce radiation (excluding cooling radiation) in X-rays and also to form PWN, there must be ejection of high-energy particles. The production of these kinds of radiation and PWN must depend on different parameters of neutron star. Note that the magnetic field may not be pure magneto-dipole field and the angle between the magnetic field and the spin axis is uncertain. These facts also make the solution of the problems more difficult. We want to figure out whether X-ray radiation of pulsars and the formation of PWN depend on  $\dot{E}$  or the electric field intensity ( $E_{el}$ ) more strongly for the case of pure magneto-dipole radiation. In order to clarify these problems, we have constructed X-ray luminosity (2-10 keV) versus  $\dot{E}$  diagram for all radio and single X-ray pulsars with characteristic time ( $\tau$ )  $< 10^6$  yr located up to 7 kpc from the Sun including also 2 pulsars in Magellanic Clouds (Figure 1). The data of these pulsars are represented in Table 1.

Depending on values of the magnetic field and the speed of rotation on the surface of neutron star, there arises induced electric field of which the intensity is represented as <sup>4</sup>:

$$E_{el} = \frac{4\pi R B_r}{c} \frac{\dot{P}}{P} \sim \left(\frac{\dot{P}}{P}\right)^{\frac{1}{2}} \quad (1)$$

where  $R$  is the radius of neutron star,  $B_r$  the value of the real magnetic field strength and  $c$  the speed of light. In actuality, pulsars are located in plasma and expression (1) does not give the exact value of  $E_{el}$ . As the  $P$ - $\dot{P}$  diagram which we use is always represented in logarithmic scale, the lines of constant  $E_{el}$  pass parallel to the lines of constant characteristic time

$$\tau = \frac{P}{2\dot{P}} \quad (2)$$

so that, we do not show the lines of  $E_{el}=\text{constant}$  on the  $P$ - $\dot{P}$  diagram. Calculated values of  $E_{el}$  may also contain some mistakes, because different pulsars may have different radius, moment of inertia ( $I$ ) and braking index.

Often, there is PWN around the youngest pulsars which we include in Table 1. For such cases the X-ray luminosity value include both the X-ray radiation of the pulsar and of the PWN in most of the cases, as it is difficult to distinguish the  $L_x(\text{PWN})$  part of the luminosity. On the other hand, since the contribution of the PWN to the X-ray luminosity can be at most comparable with the X-ray luminosity of the pulsar in general <sup>3</sup>, the change in the positions of the pulsars in the figures will be small in such cases that the dependences found from the best fits do not change considerably. It must also be noted that the uncertainties in the distance values and in the measured 2-10 keV fluxes can not have significant influences on these dependences. The pulsars with  $\tau < 10^6$  yr located up to 7 kpc for which the X-ray luminosity only in the 0.1-2.4 keV band is known are also displayed in Table 1. We have adopted reliable values of distance for the pulsars <sup>5</sup> and X-ray luminosity data mainly have been taken from Possenti et al. <sup>2</sup> and Becker & Aschenbach <sup>3</sup>.

The dependence between X-ray luminosity (2-10 keV) and  $\dot{E}$  is displayed in Figure 1. The equation of this dependence is:

$$L_{2-10\text{keV}} = 10^{-23.40 \pm 4.44} \dot{E}^{1.56 \pm 0.12}. \quad (3)$$

In Figure 2, X-ray luminosity (2-10 keV) versus  $\tau$  diagram is represented for the same pulsar sample shown in Figure 1. The equation for the relation between X-ray luminosity (2-10 keV) and  $\tau$  is:

$$L_{2-10\text{keV}} = 10^{41.79 \pm 1.04} \tau^{-1.98 \pm 0.23}. \quad (4)$$

As seen from Figures 1 and 2, the deviations of the data with respect to the best fits shown in the figures are larger in the  $L_x$  (2-10 keV) versus  $\tau$  diagram compared to the  $L_x$  (2-10 keV) versus  $\dot{E}$  diagram, but there is no significant difference.

Some pulsars in Table 1 have  $\gamma$ -ray radiation. As seen from Figure 1, these pulsars are in general located below the best fit line. On the other hand, all the pulsars with large effective magnetic field ( $B$ ) values ( $\log B > 12.7$ ) are located above the line (note that when there exist some additional mechanisms other than the magneto-dipole mechanism,  $B > B_r$ ). We have not designated these pulsars in Figure 2 but notice that  $\gamma$ -ray pulsars in this figure are located in both parts with respect to the best fit line, whereas, all the pulsars with large values of  $B$  have positions below the line. This is

also the result of different dependences of  $E_{el}$  (see expression (1)) and rate of rotational energy loss

$$\dot{E} = \frac{4\pi^2 I \dot{P}}{P^3}, \quad (5)$$

on the value of  $P$  (note that in this approximation we neglect the dependences of the observational and the calculated parameters of pulsars on the radius and mass of neutron stars).

Which parameters of neutron stars do the deviations in Figures 1 and 2 mainly depend on? In order to understand this, we have examined pulsars in narrow  $\dot{E}$  intervals with large differences in their  $L_x$  values which lead to large deviations. The largest deviation is for the interval  $\log \dot{E}=36.78-36.9$  where pulsars J1846-0258, J1811-1925, and Vela are present. These are not ordinary pulsars: pulsars J1846-0258 and J1811-1925 are strong X-ray pulsars which have not been detected in other bands, whereas, Vela pulsar, which has been known as a radio, optical and gamma-ray pulsar until recently, has been identified also in X-rays but with low luminosity <sup>6</sup>. The  $L_x$  (2-10 keV) value of Vela pulsar (Table 1) is more than one order of magnitude larger than the value given by Possenti et al. <sup>2</sup>. This is because we have also included the X-ray luminosity of the PWN around the Vela pulsar which is about 10 times greater than the X-ray luminosity of the pulsar <sup>7</sup> and we have adopted a more reliable distance value <sup>5</sup> so that the luminosity value also increased about 3 times. Despite these facts, the position of Vela pulsar in Figure 1 is still well below the line and the difference between the luminosity values of Vela pulsar and pulsar J1846-0258 is still very large. Although, the period value of pulsar J1846-0258 is 4-5 times larger than the period values of Vela pulsar and pulsar 1811-1925, since the magnetic field

$$B = \sqrt{\frac{3c^3 I P \dot{P}}{8\pi^2 R^6}} \quad (6)$$

and  $\dot{E}$  values of pulsar J1846-0258 are larger than the values of the other two pulsars (even though the  $\tau$  value is small), its luminosity (2-10 keV) value is larger (see Table 1).

The second largest deviation among large  $\dot{E}$  values in Figure 1 is in the  $\log \dot{E}=37.21-37.42$  interval where pulsars J1513-5908, J0205+6449, J1617-5055, and J2229+6114 are located in. Pulsar J1513-5908, the youngest one among these pulsars, has the largest  $P$ ,  $B$  and  $L_x$  values. Among the other

pulsars in this group, the largest  $\dot{E}$  value belongs to pulsar J0205+6449 in this interval and this pulsar has a smaller value of  $\tau$ , a larger value of  $B$ , and a period value in between the values of pulsars J1617-5055 and J2229+6114. In spite of this, the luminosity of this pulsar is less than the luminosity of pulsar J1617-5055. This is strange, because all four parameters ( $P$ ,  $\tau$ ,  $B$ ,  $\dot{E}$ ) of pulsar J0205+6449 suggest a larger luminosity value. Furthermore, there is no supernova shell or PWN around pulsar J1617-5055. This contradiction is not because of the adopted distance values. Is this contradiction related to the uncertainties in the observational data? Although, the luminosity values of these 2 pulsars (J0205+6449 and J1617-5055) are comparable within error limits <sup>2</sup>, one still can not explain why pulsar J0205+6449 does not have a larger  $L_x$  value. If the observational data are not significantly different than the actual values, then either there may be a considerable difference in the mass values of these 2 pulsars or the magnetic field may not be pure dipole.

Among the youngest pulsars, the largest deviations are in the  $\log \tau=3.19$ - $3.22$  interval. Among the pulsars in this interval, the smallest  $P$  and the largest  $\dot{E}$  values belong to pulsar J0540-6919 which has also the largest  $L_x$  value. In this interval, the smallest  $L_x$  value belongs to pulsar J1119-6127 which has the largest  $P$  and  $B$  values and the smallest  $\dot{E}$  value. According to Gonzalez & Safi-Harb <sup>8</sup>, J1119-6127 has unabsorbed  $L_x$  (0.5-10 keV)  $=5.5^{+10}_{-3.3} \times 10^{32}$  erg/s at 6 kpc. There is no pulsed X-ray radiation observed from radio pulsar J1119-6127 and the position of the X-ray source is not coincident with the position of the radio pulsar; the observed point source may actually be a PWN <sup>9</sup>.

Pulsar J0358+5413 has  $\log \tau=5.75$  and pulsar J0538+2817 has  $\log \tau=5.79$ . The  $L_x$  value of pulsar J0358+5413 is about 300 times larger than the  $L_x$  value of pulsar J0538+2817, but the  $P$ ,  $B$  and  $\dot{E}$  values of these 2 pulsars are roughly the same. Why is pulsar J0358+5413 much more luminous than pulsar J0538+2817? The absolute error of the  $L_x$  (2-10 keV) value of pulsar J0358+5413 is very large <sup>2</sup> and the  $L_x$  (2-10 keV) value is not a directly measured value but converted by Possenti et al. <sup>2</sup> from the  $L_x$  value in softer band <sup>10</sup>. So, the high  $L_x$  (2-10 keV) value of pulsar J0358+5413 can actually be much lower and the large difference in the  $L_x$  (2-10 keV) values of pulsars J0358+5413 and J0538+2817 can actually be much smaller.

If we consider the corrections to the positions of some of the pulsars discussed above taking also into account relations between  $L_x$  and  $\dot{E}$ ,  $\tau$ ,  $B$  and  $P$ , and if we change the positions of the pulsars in the figures within

error limits given in Possenti et al. <sup>2</sup> then, pulsar J1119-6127 will have a higher  $L_x$  value, whereas, pulsars J1826-1334, J1302-6350 and J0358+5413 will have lower values of  $L_x$ . In this case, the dependence between  $L_x$  and  $\tau$  given in eqn.(4) will be improved with a more negative power of  $\tau$ . If we apply the same approach for the positions of some of the pulsars in Figure 1, we see that the deviations do not decrease and the power of  $\dot{E}$  (eqn.(3)) increases negligibly.

Some of the pulsars shown in Figures 1,2 and in Table 1 have experienced strong glitches ( $\frac{\Delta P}{P} > 10^{-6}$ , denoted with 'G' in Figure 2). As seen from Figure 2, the deviations of the data do not seem to be due to the glitch activity.

### 3 The evolutionary factors

Since the values of  $P$  and  $\dot{P}$  and the other parameters change continuously during the pulsar evolution, the value of  $L_{2-10keV}$  must also change in connection to this. We want to analyse how the  $L_{2-10keV}$  luminosity of pulsars changes during the evolution of pulsars on the  $P$ - $\dot{P}$  diagram.

From eqn. (3) we see that

$$L_{2-10keV}^{(\dot{E})} \propto \left(\frac{\dot{P}}{P^3}\right)^{1.56} \quad (7)$$

and similarly from eqn. (4)

$$L_{2-10keV}^{(\tau)} \propto \left(\frac{\dot{P}}{P}\right)^{1.98} \quad (8)$$

using the expressions for  $\dot{E}$  (5) and  $\tau$  (2). Now, using the expression for  $B$  (6), we can write (7) and (8) in the form:

$$L_{2-10keV}^{(\dot{E})} \propto \left(\frac{B^2}{P^4}\right)^{1.56} \quad (9)$$

and

$$L_{2-10keV}^{(\tau)} \propto \left(\frac{B^2}{P^2}\right)^{1.98}. \quad (10)$$

If both dependences (3) and (4) are applicable in finding the value of  $L_x$ , then the ratio of the luminosities for each pulsar found from equations (9)

and (10) must roughly be the same throughout the evolution of a pulsar. From dependences (10) and (9) we get:

$$\frac{L_{2-10keV}^{(\tau)}}{L_{2-10keV}^{(\dot{E})}} \propto B^{0.84} P^{2.28}. \quad (11)$$

So, the ratio is strongly dependent on  $P$  which must be wrong because the ratio must not change significantly during the evolution if both dependences are reliable.

X-ray luminosity of the considered pulsars strongly depends on different parameters of pulsars and decreases with age down to  $L_x \sim 10^{29}-10^{30}$  erg/s. During the evolution of these pulsars, the period value changes up to a factor of 10,  $\dot{P}$  up to 50 times,  $\dot{E}$  up to  $10^4$  times, and  $\tau$  up to 500 times. During the evolution, value of  $B$  for each pulsar may decrease only up to a factor of 3, but magnitudes of the deviation of  $B$  values for different pulsars are larger.

As seen from Figure 5, an increase in the initial magnetic field value of a factor of 10 leads to a decrease in the age of X-ray pulsar of a factor of 10. As X-ray luminosity of young pulsars strongly depends on  $E_{el}$  and  $\dot{E}$ , as seen from the  $L_x$ - $\tau$  diagram (Figure 2) and Figure 5, the X-ray luminosity of the pulsars with largest initial  $B$  values drop very quickly below the threshold during the evolution, whereas, the X-ray luminosity of the pulsars with smaller initial values of  $B$  last longer and drop below the threshold in about  $10^5$  yr. Therefore, it is necessary to consider a more homogeneous group of pulsars which have  $B$  values close to each other. Naturally, the best fit lines for the new sample must lead to a different equation for the  $L_x$ - $\tau$  dependence and practically the same equation for the  $L_x$ - $\dot{E}$  dependence. In order to see this, we have constructed  $L_x$  vs.  $\dot{E}$  and  $L_x$  vs.  $\tau$  diagrams (Figures 3 and 4) for the pulsars with  $B$  values in the interval  $12.2 \leq \log B \leq 12.7$  (Figure 5). Again from the best fits, we get dependences between  $L_x$  and  $\dot{E}$ :

$$L_{2-10keV} = 10^{-27.46 \pm 6.48} \dot{E}^{1.66 \pm 0.18} \quad (12)$$

and  $L_x$  and  $\tau$ :

$$L_{2-10keV} = 10^{45.98 \pm 1.51} \tau^{-2.99 \pm 0.36}. \quad (13)$$

From these two dependences it is seen that the dependence given by eqn.(3) is comparable to the dependence given by eqn.(12) within error limits, but the dependence given by eqn.(4) changed considerably (see eqn.(13)).

Dividing eqn.(13) by eqn.(12) and again using the expressions (5) and (2) we get:

$$\frac{L_{2-10keV}^{(\tau)}}{L_{2-10keV}^{(\dot{E})}} \propto B^{2.66} P^{0.66}. \quad (14)$$

As the effective B value decreases gradually during the evolution, the large increase in the P value compensates it and the ratio remains approximately the same. The dependences (12) and (13) are more reliable and reflect the evolutionary effects, because we have used a more homogeneous group of pulsars with similar evolutionary tracks in Figures 3 and 4. The ratio given by dependence (14) shows this fact.

The reason of the considerable difference between the dependences (4) and (13) can easily be seen in Figure 5. As seen from this figure, when the value of  $\tau$  is small, first the constant  $\tau$  line crosses the considered B interval (i.e. the interval of  $12.2 \leq \log B \leq 12.7$ ) where the value of  $\dot{E}$  is large. Then, it crosses the region, which is not included in the B interval under consideration, where the value of  $\dot{E}$  is small. On the other hand, if the value of  $\tau$  is large, then the constant  $\tau$  line first crosses a region, outside the considered B interval, where pulsars with large values of  $\dot{E}$  are located, and then it crosses the B interval under consideration where pulsars with small  $\dot{E}$  values are present. Therefore, for small values of  $\tau$ , the pulsars which have smaller values of  $L_{2-10keV}$  and which are not located in the considered interval have positions below the best fit line in Figure 4. On the other hand, for large values of  $\tau$ , the pulsars which have larger values of  $L_{2-10keV}$  and which are not located in the considered interval have positions above the best fit line in Figure 4. Excluding the pulsars with large deviations from the best fit line leads to the considerable difference between the dependences (4) and (13).

In Table 1, we have also included the 15 pulsars with  $\tau < 10^5$  yr and/or  $\log \dot{E} > 35.60$  from which no X-ray radiation has been detected. In Figure 5, all the 48 pulsars in Table 1 are displayed. Within and around this region of the P- $\dot{P}$  diagram, there are pulsars with detected X-ray radiation. All of these pulsars without detected X-ray radiation are also located at  $d \leq 7$  kpc from the Sun. One of these pulsars is connected to a supernova remnant (SNR).

As seen from Figure 5 and Table 1, there are some pulsars without observed X-ray radiation which have smaller  $\tau$  values and larger  $\dot{E}$  values compared to some pulsars with observed X-ray radiation. What is the reason

for not detecting X-ray radiation from such pulsars? As mentioned in the previous section, the X-ray luminosity must depend not only on  $P$  and  $\dot{P}$  but also on some other parameters. The deviations of the data from the best fits in Figures 1-4 also show this fact. It is not easy to examine these "other parameters" which can not be calculated from values of  $P$  and  $\dot{P}$  and get reliable results. But it is possible to clarify why there exist those pulsars with smaller  $\tau$  values and larger  $\dot{E}$  values from which no X-ray radiation has been detected by examining the selection effects.

It is clear that it is more difficult to observe the X-ray radiation of a pulsar if it is located at a large distance in the Galactic plane and in the Galactic centre direction. All the 8 pulsars with  $\tau > 10^5$  yr from which X-ray radiation has been observed as shown in Figure 5 are located at distances  $d < 2.5$  kpc from the Sun (Figure 6). Directions of these and all the other pulsars in Table 1 are shown in  $b$  vs.  $l$  diagram (Figure 7).

In Figure 6,  $\dot{E}$ - $d$  diagram for all the 48 pulsars in Table 1 is represented. The pulsars without observed X-ray radiation are all located beyond 2 kpc from the Sun. It is normal to detect X-ray radiation from pulsars with large  $\dot{E}$  values even at large distances (see Figure 6), but there is a pulsar, namely J0631+1036, with detected X-ray radiation in the 2-10 keV band which is located at  $d = 6.6$  kpc and has a smaller  $\dot{E}$  value ( $\log \dot{E} = 35.24$ ). The reason for this is that this pulsar is located in the Galactic anti-centre direction (see Figure 7). The other 8 pulsars with detected X-ray radiation and with distances between 6-7 kpc are located in the Galactic central directions. Six out of the 8 far away pulsars in the central directions are connected to SNRs that these are well examined pulsars. So, it must be considered normal to detect the X-ray radiation of these pulsars. On the other hand, the remaining 2 pulsars, namely J1105-6107 and J1617-5055, are not connected to SNRs. Pulsar J1617-5055 has very high  $\dot{E}$  and large  $L_x$  values (see Table 1), and pulsar J1105-6107 is located in between the Sagittarius and the Scutum arms so that it is normal to observe the X-ray emission of these 2 pulsars. All the pulsars without detected X-ray radiation are located in the central directions and in the directions of Vela OB-associations (see Figure 7). Moreover, the pulsars with  $d \leq 4.1$  kpc which have not been detected in X-rays (J0940-5428, J1809-1917, J1718-3825, J1531-5610, J1509-5850, J1913+1011) have all been found in recent pulsar surveys<sup>11,12,13</sup>. In the near future, it is possible that all of these pulsars will be detected in X-rays.

## 4 Discussion and Conclusions

For single pulsars, the X-ray radiation due to the relativistic particles, which considerably exceeds the cooling radiation, is important and worth examining. Power and spectrum of this radiation depend on the number and the energy spectra of the relativistic electrons in the magnetospheres of pulsars. They also depend on the number density of charged particles and the magnetic field in the magnetosphere. The X-ray radiation of PWNe also depends on these quantities. X-ray radiation has also been observed from old single millisecond pulsars which is absolutely not cooling radiation but a result of Coulomb interaction between the accelerated particles and the charged particles in the magnetosphere. Since the parameters of millisecond pulsars practically do not vary in time and as they are not active as the young pulsars are, we do not consider them in this work.

From the investigations of single pulsars which radiate X-rays as a result of ejection of relativistic particles, we have concluded as follows:

- 1) Luminosity in 2-10 keV band (often the total luminosity including the luminosity of the PWN) strongly depends on electric field intensity  $E_{el}$  (or  $\tau$ ), rate of rotational energy loss  $\dot{E}$ , magnetic field  $B$ , period, and in smaller degree on some other parameters of neutron stars.
- 2) The dependence of  $L_x$  on  $\dot{E}$  is practically the same for pulsars with very different values of  $B$  and with  $B=10^{12}$ - $10^{13}$  G. This is not true for the  $L_x$ - $\tau$  dependence.
- 3) Pulsars with different initial values of  $B$  and with  $\tau$  about  $10^3$  yr begin to evolve from different points of the  $L_x$ - $\dot{E}$  dependence and then continue to evolve with similar trajectories until  $L_x$  drops to  $\sim 10^{30}$  erg/s, but the same pulsars begin and end their evolution in different parts of the  $L_x$ - $\tau$  dependence and the evolutionary tracks are not parallel to the  $L_x$ - $\tau$  dependence for all the pulsars under consideration.
- 4) The pulsars, which also radiate gamma-rays, with the same values of  $\dot{E}$  as the other pulsars without gamma-ray radiation have several times smaller X-ray luminosities.
- 5) The pulsars which have PWNe practically always have X-ray luminosities greater than  $10^{33}$  erg/s.
- 6) Practically, values of  $\tau$  and  $\dot{E}$  determine the X-ray luminosity. The increase in  $\tau$  and the decrease in  $\dot{E}$  simultaneously lead to a rapid decrease in  $L_x$ . Value of  $L_x$  decreases from  $\sim 10^{37}$  erg/s for  $\dot{E} \sim 3 \times 10^{38}$  erg/s and  $\tau \sim 10^3$  yr to

$\sim 10^{30}$  erg/s for  $\dot{E} \sim 3 \times 10^{34}$  erg/s and  $\tau \sim 3 \times 10^5$  yr.

If we take into account these and also the strength and spectra of the X-ray radiation of millisecond pulsars <sup>2,3</sup>, we can have some preliminary conclusions about the acceleration of particles and their radiation. As the characteristic time of millisecond pulsars is about 4-5 orders of magnitude smaller compared to the young pulsars, their  $E_{el}$  values must be 200-250 times smaller than the  $E_{el}$  values of young pulsars. On the other hand, the value of  $E_{el}$  does not have a strong influence on the X-ray radiation of pulsars. The X-ray spectra of young pulsars are, on average, steeper compared to the spectra of millisecond pulsars. If we also consider the strong dependence of the X-ray radiation of all the pulsars on the value of  $\dot{E}$ , we can conclude as follows:

- 7) Acceleration of particles mainly takes place in the field of magnetodipole radiation wave.  $E_{el}$  has a role of only triggering this process.
- 8) The high values of X-ray luminosity of young pulsars under the same  $\dot{E}$  values and the steeper spectra of such pulsars are related to the large amount of charged particles in their magnetospheres as compared to millisecond pulsars.

It is necessary to reexamine the X-ray flux values of J0205+6449, J0358+5413, and J0538+2817 in 2-10 keV band to understand the dependences of the X-ray luminosity on  $\dot{E}$ ,  $E_{el}$ ,  $B$  and  $P$  values and the possible dependence on the energy spectra of the ejected particles.

Also, in order to understand the dependence of the X-ray radiation on different parameters of pulsars better, it is necessary to observe pulsars J0940-5428, J1809-1917, J1718-3825, J1531-5610, J1509-5850, J1913+1011 preferably in the hard X-ray band.

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**Table 1 - All 33 radio and X-ray pulsars with detected X-ray radiation in 0.1-2.4 keV and/or in 2-10 keV bands and with  $\tau < 10^6$  yr. All 15 pulsars which have  $\text{Log } \dot{E} > 35.6$  and  $\tau < 10^5$  yr. All pulsars which are connected to SNRs (PWNe). Two of these pulsars are in Magellanic Clouds and the others are Galactic pulsars with  $d \leq 7$  kpc. In the first column 'G' denotes strong glitch. In column 12  $\beta = 2\Delta\theta/\theta$  ( $\theta$ : SNR diameter,  $\Delta\theta$ : angular distance of pulsar from the geometric centre of SNR).**

	JName	Type	d kpc	P s	P s/s	Log $\tau$	Log B	Log $\dot{E}$	SNR + l,b	Type	$\beta$	Log $L_x$ 0.1-2.4 keV	Log $L_x$ 2-10 keV
	J1846-0258	X	6.7	0.325	7.1E-12	2.859	13.70	36.9	G29.7-0.3	C	$\sim 0^{15}$	$\sim 35.18$	35.32
	J0534+2200	ROXG	2.0	0.034	4.21E-13	3.101	12.58	38.64	Crab	F	$\sim 0.19^{16}$	35.98	36.65
	J1513-5908	RXG	4.2	0.151	1.54E-12	3.191	13.19	37.25	G320.4-1.2	C	$0.24^{16}$	34.25	35.32
	J1119-6127	RX	7.0	0.408	4.02E-12	3.205	13.61	36.37	G292.2-0.5	C	$\sim 0^{17}$	$\leq 32.5$	33.42
	J0540-6919	ROX	50	0.051	4.79E-13	3.222	12.70	38.17	N158A	C	$\sim 0^{18}$	36.21	36.93
	J1124-5916	RX	6.0	0.135	7.45E-13	3.458	13.01	37.07	G292.0+1.8	C		$\sim 32.7$	34.67
	J1930+1852	RX	7	0.137	7.51E-13	3.462	13.0	37.23	G54.1+0.3	F		$\sim 34.2$	
	J0537-6910	RX	50	0.016	5.1E-14	3.7	12.0	38.7	N157B	F		$\sim 36.0$	36.11
	J0205+6449	RX	3.2	0.066	1.9E-13	3.740	12.55	37.42	G130.7+3.1	F		32.38	34.26
G	J1617-5055	RX	6.2	0.069	1.371E-13	3.903	12.49	37.21	332.5,-0.27			34.30	34.59
	J2229+6114	RXG	5.5	0.052	7.8E-14	4.023	12.31	37.34	G106.6+2.9	C	$0^{19}$	33.58	33.69
G	J0835-4510	ROXG	0.40	0.089	1.25E-13	4.054	12.53	36.84	Vela	C	$0.29, 0.3^{16,17}$	32.46	33.18
	J1420-6048	RXG	6.1	0.068	8.32E-14	4.113	12.38	37.01	G313.4+0.2?	F	$0.2^{20}$	34.26	34.30
G	J1801-2451	RX	4.5	0.125	1.284E-13	4.189	12.61	36.41	G5.27-0.9	F	$\sim 0^{21}$	$\sim 33.0$	33.18
G	J1803-2137	RX	3.5	0.134	1.34E-13	4.197	12.63	36.35	G8.7-0.1	S?	$0.7^{22}$	33.06	32.39
	J1702-4310	R	4.8	0.2405	2.24E-13	4.23	12.88	35.80	343.4,-0.85				
G	J1709-4428	RXG	1.8	0.102	9.30E-14	4.241	12.49	36.53	G343.1-2.3?			33.15	32.58
	J1856+0113	RX	2.8	0.267	2.08E-13	4.308	12.88	35.63	G34.7-0.4	C	$0.51^{16}; 0.6^{17}$	$\leq 33.0$	33.03
	J1048-5832	RXG	2.8	0.124	9.63E-14	4.308	12.54	36.30	287.4,+0.58			$\leq 32.11$	32.35
	J1016-5857	RX	6.5	0.107	8.11E-14	4.321	12.48	36.41	G284.3-1.8	S	$1^{20}; 1.3^{23}$	$\sim 33.5$	
G	J1826-1334	RX	3.4	0.101	7.55E-14	4.328	12.45	36.45	G18.0-0.7	F		$\sim 32.7$	34.34
	J1811-1925	X	5	0.065	4.22E-14	4.4	12.23	36.78	G11.2-0.3	F	$\sim 0^{24}$	32.8	34.54
	J1747-2958	RX	2.0	0.099	6.14E-14	4.41	12.41	36.41	G359.2-0.8?	F		$\sim 34.0$	
G	J1730-3350	R	4.24	0.1394	8.51E-14	4.41	12.56	36.09	354.1,+0.09				
	J1646-4346	R	6.9	0.232	1.13E-13	4.51	12.71	35.55	G341.2+0.9	C	$0.7^{22}$		
	J1837-0604	R	6.2	0.0963	4.52E-14	4.53	12.34	36.30	26.0,+0.27				
	J1015-5719	R	4.87	0.1399	5.74E-14	4.59	12.47	35.92	283.1,-0.58				
	J2337+6151	RX	2.8	0.495	1.92E-13	4.611	12.99	34.79	G114.3+0.3	S	$0.08^{16,25}$	31.90	31.47
	J1637-4642	R	5.5	0.1540	5.92E-14	4.62	12.50	35.81	337.8,+0.31				
	J0940-5428	R	3.8	0.0875	3.29E-14	4.63	12.25	36.29	277.5,-1.29				
	J0631+1036	RX	6.6	0.288	1.05E-13	4.639	12.74	35.24	201.2,+0.45				31.90
	J1809-1917	R	3.3	0.0827	2.55E-14	4.71	12.18	36.25	11.1,+0.08				
	J1105-6107	RX	7.0	0.063	1.58E-14	4.801	12.01	36.39	290.5,-0.85			$\sim 33.2$	33.55
	J1718-3825	R	3.3	0.0747	1.32E-14	4.95	12.02	36.10	348.9,-0.43				
	J1531-5610	R	2.6	0.0842	1.37E-14	4.99	12.05	35.96	323.9,+0.03				
	J1952+3252	RXG	2.0	0.040	5.84E-15	5.030	11.69	36.57	G69.0+2.7	?	$0.14, 0.15^{16,17}$	33.64	33.07
	J0659+1414	ROX	0.6	0.385	5.50E-14	5.044	12.67	34.58	G201.1+8.7			32.78	30.92
	J0908-4913	R	4.5	0.1068	1.51E-14	5.05	12.12	35.69	270.3,-1.02				
	J0855-4644	R	6.4	0.0647	7.26E-15	5.15	11.85	36.03	267.0,-1.0				
G	J1833-0827	R	5.67	0.0853	9.17E-15	5.17	11.97	35.77	23.4,+0.06				
	J1509-5850	R	2.5	0.0889	9.17E-15	5.19	11.97	35.71	320.0,-0.62				
	J1913+1011	R	4.1	0.0359	3.37E-15	5.23	11.56	36.46	44.5,-0.17				
	J0117+5914	RX	2.4	0.101	5.85E-15	5.44	11.89	35.34	126.3,-3.46				30.44
Be	J1302-6350	RX	1.3	0.048	2.28E-15	5.52	11.52	35.92	304.2,-1.00				32.57
	Geminga	X	0.15	0.237	1.14E-14	5.53	12.22	34.53	195.13,+4.27				29.33
	J1057-5226	RX	1.0	0.197	5.83E-15	5.73	12.04	34.48	286.0,+6.65			33.13	30.08
G	J0358+5413	RX	2	0.156	4.4E-15	5.75	11.92	34.66	148.2,+0.81				31.75
	J0538+2817	RX	1.5	0.143	3.67E-15	5.79	11.87	34.69	G180.0-1.7?	C		32.74	29.31

### Figure Captions

**Figure 1:** Log  $L_x$  (2-10 keV) versus log  $\dot{E}$  diagram of all 30 pulsars with  $\tau < 10^6$  yr which have observed X-ray radiation. 28 of these pulsars are located up to 7 kpc from the Sun and 2 of them are in Magellanic Clouds. 'Plus' signs denote the 2 pulsars in Magellanic Clouds. 'Cross' signs show the positions of pulsars with  $10^5 < \tau < 10^6$  yr and 'star' signs show the positions of pulsars with  $\tau < 10^5$  yr. 'Square' signs denote single X-ray pulsars. Seven of these pulsars have  $\log B > 12.7$  (denoted with 'B') and from 8 of them  $\gamma$ -rays have been observed (denoted with 'G').

**Figure 2:** Log  $L_x$  (2-10 keV) versus log  $\tau$  diagram of all 30 pulsars with  $\tau < 10^6$  yr which have observed X-ray radiation. 28 of these pulsars are located up to 7 kpc from the Sun and 2 of them are in Magellanic clouds. 'Plus' signs denote the 2 pulsars in Magellanic Clouds. 'Cross' signs show the positions of pulsars with  $10^5 < \tau < 10^6$  yr and 'star' signs show the positions of pulsars with  $\tau < 10^5$  yr. 'Square' signs denote single X-ray pulsars. Seven of these pulsars have experienced strong ( $\Delta P/P > 10^{-6}$ ) glitches (denoted with 'G').

**Figure 3:** Log  $L_x$  (2-10 keV) versus log  $\dot{E}$  diagram for 15 of the 30 pulsars shown in Figures 1 and 2; these 15 pulsars have  $12.2 \leq \log B \leq 12.7$ . 'Plus' sign denotes the pulsar in Magellanic Cloud. 'Cross' signs show the positions of pulsars with  $10^5 < \tau < 10^6$  yr and 'star' signs show the positions of pulsars with  $\tau < 10^5$  yr. 'Square' sign denotes the single X-ray pulsar.

**Figure 4:** Log  $L_x$  (2-10 keV) versus log  $\tau$  diagram for 15 of the 30 pulsars shown in Figures 1 and 2; these 15 pulsars have  $12.2 \leq \log B \leq 12.7$ . 'Plus' sign denotes the pulsar in Magellanic Cloud. 'Cross' signs show the positions of pulsars with  $10^5 < \tau < 10^6$  yr and 'star' signs show the positions of pulsars with  $\tau < 10^5$  yr. 'Square' sign denotes the single X-ray pulsar. Black squares show the positions of the pulsars which are present in Figure 2 but not included in the fit of Figure 4.

**Figure 5:** Period versus period derivative diagram for all 48 pulsars represented in Table 1 with  $\tau < 10^6$  yr and distance  $\leq 7$  kpc including the 2 pulsars in Magellanic Clouds. 'Circles' represent the 33 pulsars from which X-ray radiation have been detected in 2-10 keV and/or 0.1-2.4 keV bands. 'Plus' signs denote the 15 pulsars with  $\log \dot{E} > 35.55$  from which no X-ray radiation has been observed.

**Figure 6:** Log  $\dot{E}$  versus distance diagram for all 48 pulsars represented in Table 1 with  $\tau < 10^6$  yr and distance  $\leq 7$  kpc including the 2 pulsars in Magellanic Clouds. 'Circles' represent the 33 pulsars from which X-ray radi-

ation have been detected in 2-10 keV and/or 0.1-2.4 keV bands. 'Plus' signs denote the 15 pulsars with  $\log \dot{E} > 35.55$  from which no X-ray radiation has been observed. 'Cross' signs represent the 8 pulsars with  $10^5 < \tau < 10^6$  yr.

**Figure 7:** Galactic longitude (l) versus Galactic latitude (b) diagram for all 48 pulsars represented in Table 1 with  $\tau < 10^6$  yr and distance  $\leq 7$  kpc including the 2 pulsars in Magellanic Clouds. 'Circles' represent the 33 pulsars from which X-ray radiation have been detected in 2-10 keV and/or 0.1-2.4 keV bands. 'Plus' signs denote the 15 pulsars with  $\log \dot{E} > 35.55$  from which no X-ray radiation has been observed. 'Cross' signs represent the 8 pulsars with  $10^5 < \tau < 10^6$  yr.













